Large polycrystalline wafers boost SiC's prospects

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A unique chemical vapour deposition technique developed by Sullivan & Co enables the company to produce polycrystalline silicon carbide wafers with electrical characteristics comparable to single-crystal SiC. Introduced commercially in January 1999, the large, non-porous, low-density wafers offer device makers the opportunity to design and manufacture wide bandgap devices in SiC.

Single-crystal silicon carbide (SiC) wafer results can now be achieved using a particular type of oriented polycrystalline SiC that supports single crystal epilayers. Previously considered to be unachievable, this breakthrough is the result of a chemical vapour deposition (CVD) process developed by Sullivan & Co (Indianapolis, IN, USA) that rapidly deposits beta-phase (3C) polycrystalline SiC without porosity or 'micropipes' at atmospheric pressure.

Using the process, polycrystalline SiC wafers have been made exhibiting an electron carrier mobility of 370 $cm^2.V^{-1}.s^{-1}$ at a doping level of 7 x 10^{13} cm^{-3} doping – namely, the Hall Effect mobility is identical to that of 6H single-crystal SiC. Economies of scale in the material making process are rapidly reducing the prices for SiC wafers to a level expected to be competitive with silicon and gallium arsenide (GaAs) for wafer sizes up to 450 mm in volume production.

To date, the commercial development of devices exploiting the attributes of SiC has been limited by the lack of large-sized, defect-free wafers in volume production at competitive prices. Semi-insulating (>1x10^5 Ω.cm) single-crystal SiC wafers are available commercially in 2.0 inch diameters at a price of US$4750 per wafer for order quantities >4 wafers (Cree Research Inc's price list, August 1999) without any maximum guaranteed level of micropipe density. In contrast, polycrystalline SiC wafers up to 200 mm in diameter are now commercially available in large numbers from Sullivan & Co under the registered trademark DATANITE™ (Figure 1), for less than 10% of the cost of a single-crystal SiC wafer. The company has patented, or has patents pending, for a number of applications of polycrystalline, non-porous SiC to electronic devices.

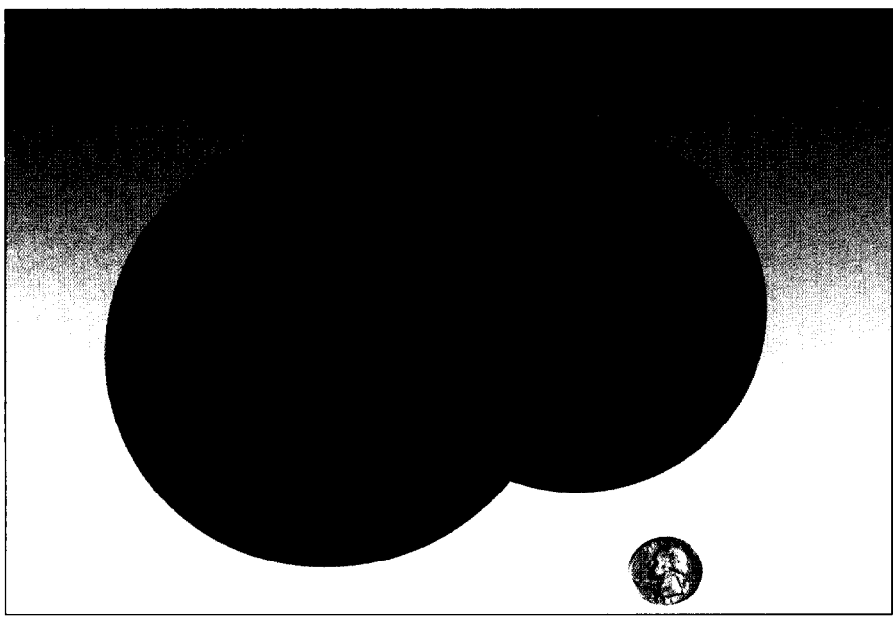

Figure 1. Sullivan & Co's 100 mm, 125 mm and 150 mm polycrystalline β-phase SiC DATANITE® wafers. The wafers support epitaxial thin films and have no micropipe defects. (Courtesy of Sullivan & Co.)

Single-crystal SiC

Silicon carbide wafers, referred to as 'single-crystal', are made by cutting a relatively defect-free segment from a larger wafer. SiC is made by a very slow, capital intensive process entailing the sublimation of SiC onto a seed crystal at very high temperatures. US Patent No. 4,866,005 describes one method of growing single-crystal SiC in which SiC powder is sublimated at 2260°C in an inert atmosphere. A SiC seed crystal is maintained at 2160°C so that the SiC vapour condenses on the surface to enlarge the seed crystal [1]. The seed crystal imparts lattice 'information' to the sublimated SiC deposited on its surface so that, as the cystal grows, the lattice structure of the SiC seed crystal is replicated. The seed crystal thereby grows to sufficient size

for slicing and mechanically polishing into wafers. However, approximately half of the initial material is lost by slicing and mechanical planarization.

In practice, SiC nucleates at many sites on a seed crystal nearly simultaneously. Nucleation sites merge as higher energy sites predominate and adsorb less energetic sites until only a few large crystals remain, usually separated by zones laden with defects. It is therefore unlikely that dramatically larger single-crystal SiC wafers at order-of-magnitude price reductions for zero-defect wafers will be available in the near future.

Moreover, at the high temperatures required for seeded sublimation, alpha-phase silicon carbide (αSiC) crystals are formed: 'αSiC' collectively refers to more than 170 polytypes of hexagonal and rhombohedral crystal shape classifications. The most common are the 6H and 4H hexagonal polytypes. Most SiC polytypes are differentiated only by small thermodynamic differences [2] which are difficult to control in a very high temperature dependent process. Unless a single crystal of a single polytype is selected, electronic properties may vary across the surface of single-crystal wafer. Though devices can be 'graded' for performance, variations add to the manufacturing steps and reduce yield.

Poly SiC wafers

While αSiC is usually a mixture of polytypes, beta-phase SiC (βSiC) has only one crystal form - 3C - which can be either mono- or polycrystalline. Sullivan's nearly amorphous, polycrystalline SiC wafers are composed of numerous face-centred cubic (FCC) 3C βSiC crystals preferentially oriented in the same direction. In no small part because of its uniform crystal composition, βSiC has uniformly high carrier mobility throughout its useful temperature range.

While the emergence of higher mobility 4H SiC has overshadowed the difficulties of heteroepitaxy of 3C SiC thin films on αSiC wafers, epitaxial 3C on a SiC substrate offers greater foundry capability and economic advantage [3].

Polycrystalline SiC wafers are oriented so that the {111} basal plane is exposed on the wafer surface, as determined by high-angle X-ray diffraction. Thin film 3C SiC on polycrystalline 3C SiC is consequently epitaxial rather than heteroepitaxial. As mentioned earlier, thin film 3C (β-phase) SiC need not be single crystal to achieve high carrier mobility.

Wafer advantages

Silicon carbide has significant advantages over silicon as a wafer material. For example, the bandgap of 3C silicon carbide wafers from experimental determination is 2.65 eV, though the bandgap of 3C epilayers on 4H or 6H single crystal wafers is 2.39 eV. By comparison, the bandgap of silicon is 1.12 eV [4]. Silicon becomes intrinsically conductive at 325°C [5], while SiC still operates as a semiconductor at 600°C [6]. A further advantage for 3C SiC is its breakdown electric field (a function of bandgap) of $2x10^6$ V.cm^{-1} for 1000 V operation, compared to $2.5x10^5$ V.cm^{-1} for silicon [4], so SiC can withstand an electric field eight times greater than silicon. In addition, SiC-based devices can operate at high frequencies because the saturated electron drift velocity of 3C SiC is low compared to silicon. In a 200 kV.cm^{-1} electric field, the drift velocity of SiC is $1.8x10^5$ m.s^{-1} compared to $1.0x10^5$ m.s^{-1} for silicon [4]. In a 300 kV.cm^{-1} electric field, silicon carbide is in a class of its own with a $1.9x10^5$ m.s^{-1} electron drift velocity [4].

For SiC the Johnson's Figure of Merit for power applications is 2533 compared to 9 for silicon, indicating that SiC is potentially 281 times better than silicon for high-frequency, high-power wafer applications. Similarly, the Keye's Figure of Merit, which relates to device density, is 90.3 for SiC compared to 13.8 for silicon, revealing that SiC is potentially 6.5 times better than silicon for wafers used for integrated circuits [4].

Table 1. Comparison of the physical properties of selected semiconductors at ambient temperature

	Si	GaAs	Epi 3C-SiC	Poly 3C-SiC	6H-SiC	4H-SiC
Bandgap (eV)	1.1	1.42	2.39	2.65	3	3.2
Breakdown field @10^{17} cm^{-3} (MV.cm^{-1})	0.6	0.6	>1.5	>1.5	3.2	3
Electron mobility @10^{16} cm^{-3} (cm^2.V^{-1}.s^{-1})	1100	6000	750	370*	370	800
Sat. electron drift velocity (cm.s^{-1})	10^7	10^7	$2.50x10^7$	$2.50x10^7$	$2.00x10^7$	$2.00x10^7$
Thermal conductivity (W.cm^{-1}.K^{-1})	1.5	0.5	4.9	Anisotropic	4.9	4.9
Hole mobility @10^{16} cm^{-3} (cm^2.V^{-1}.s^{-1})	420	320	40	Unknown	90	115
Max. size commercial wafers (in)	12	6	–	12	3	3

*Hall Effect measurement at $7x10^{13}$ cm^{-3} doping by A. Yulius and J. Woodall, Purdue University, July 1998.
Based on P.G. Neudeck, *J. Electronic Materials*, 24(2), 284.

Electronic devices formed on SiC wafers can be used at higher temperatures, at higher power levels, and under more radiation intense environments than those on silicon wafers. Die sizes for common devices can be reduced as much as 25 times to reduce cost.

Polycrystalline SiC wafers, unlike other semiconductors such as gallium arsenide or gallium nitride, have similar carrier mobility to single-crystal SiC wafers (370 $cm^2.V^{-1}.s^{-1}$;Table 1).This is believed to be because SiC is a covalently bonded material with high surface energy due to the availability of d orbitals in the silicon valence shell and the fact that the valence electrons are held less strongly by the silicon nucleus than the carbon nucleus.The weakly held valence electrons are therefore available when an electric field is applied. Moreover, overlap of p orbitals between Si and other atoms is reduced, to the extent that ordinary covalent double bonds do not exist [7].The very close bonds between individual crystals in a polycrystalline SiC body also facilitates electron mobility.

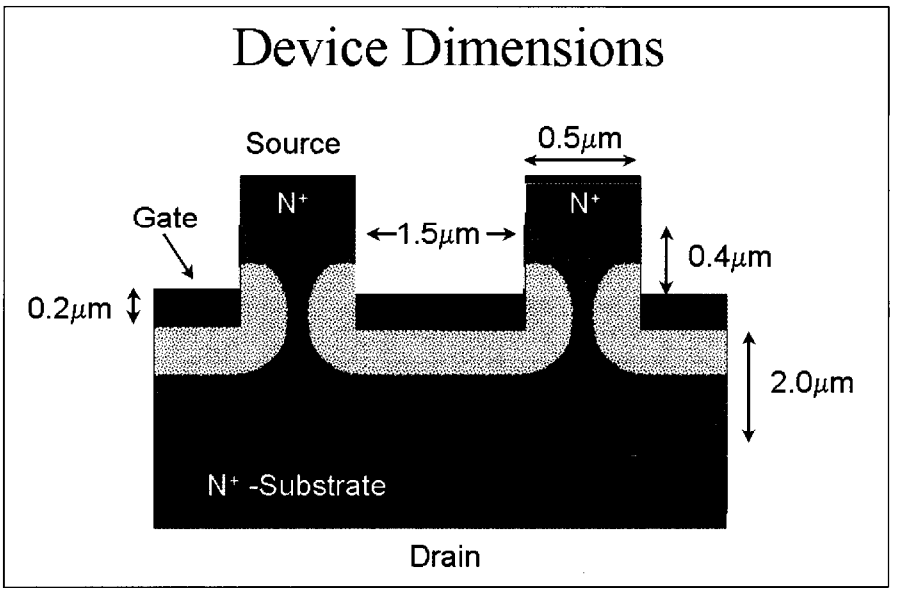

Figure 2. Schematic of a static induction transistor (SIT) device illustrating the use of a polycrystalline SiC as a substrate with single crystal SiC epilayers.

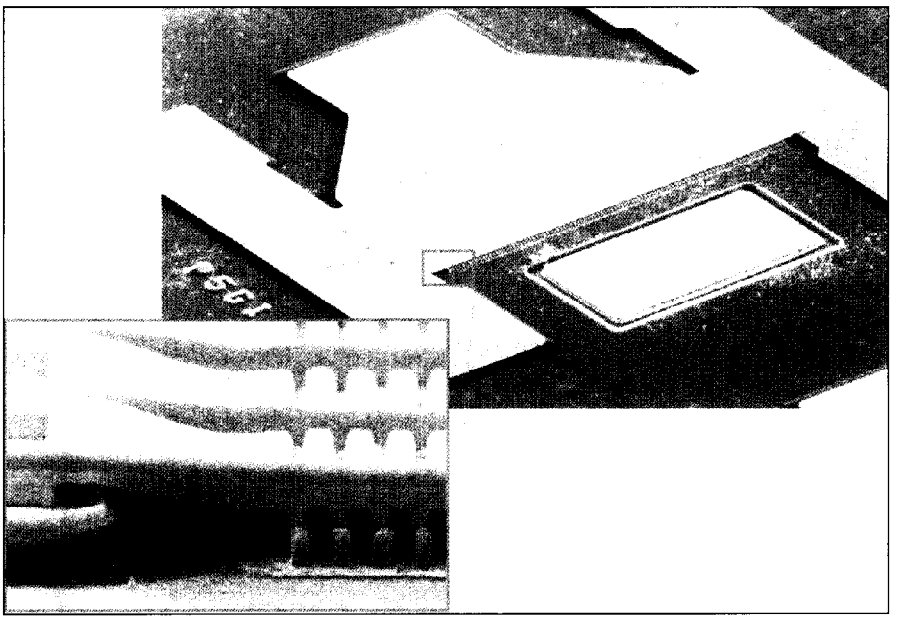

Figure 3. C-band SIT structure showing a series of 0.5 μm wide trenches separating source contacts. Metallized gates lie at the bottoms of trenches. The airbridge structure was formed by E-beam lithography. (Courtesy of Purdue University.)

Device applications

Devices made using SiC wafers have demonstrated superior performance compared to silicon due to wider bandgap, higher breakdown electric field strength, higher drift velocity at very high frequency, and greater thermal stability - attributes shared by both monocrystalline and polycrystalline SiC.

Devices have been demonstrated in SiC substrates that could not be made in any other material. Researchers at Purdue University's School of Electrical and Computer Engineering, for example, have used SiC to form a novel UMOS accumulation-channel FET (ACCUFET) having a blocking voltage of 1400 V at a specific on-resistance of 15.7 $m\Omega.cm^2$. The figure-of-merit, V_B^2/R_{ON}, of 125 $MW.cm^{-2}$ is 25 times higher than the theoretical limit for silicon power MOSFETs.

Pursuing the goal of a high power SiC linear microwave amplifier device, Purdue researchers recently demonstrated static induction transistors (SITs) for high frequency, high power microwave systems in SiC wafers (Figure 2). SITs with 0.5-1.5 μm mesas have maximum drain voltages up to 250 V with 200 $kW.cm^{-2}$ current density. Blocking gain is 10. SIT devices in SiC have operated at frequencies up to 9 GHz, well above the capability of silicon or any other substrate material. High power at high frequency is achieved by connecting multitudes of mesas on a wafer face (Figure 3), almost like the discrete devices of an integrated circuit. The die size or footprint of SIT devices

therefore increases as operational frequency increases. Larger sized polycrystalline SiC wafers without micropipes consequently become more important as the need for greater power at higher microwave frequency grows.

Submicron T-gate MESFETs in SiC have been developed to amplify microwave power. One such device, again developed by researchers at Purdue University, demonstrated saturated drain current of 350 $mA.mm^{-1}$, transconductance of 20 $mS.mm^{-1}$, drain breakdown voltage of 120 V, and maximum available RF power density of 3.2 $W.mm^{-1}$ for 0.5 μm T-gates.

Another potential application is in Schottky barrier diodes (SBDs). High voltage transients are induced in electric lines as inductive loads are applied, such as electric motors or transformers. SBDs are used as high-voltage rectifiers in power switching applications to lock out voltage excursions. Unlike PN junction diodes, SBDs dissipate negligible power during high speed switching. Nevertheless, half the cost of SBDs made in silicon wafers is attributable to heat dissipation technology.

With SiC, however, the breakdown electric field strength is eight times higher than silicon and it also has a very wide bandgap and high thermal stability. SiC SBDs can therefore operate at much higher voltages and amperages than silicon SBDs. Blocking voltage of 4.9 kV and specific on-resistance of 43 $m\Omega.cm^2$ have been demonstrated. Tests conducted by Harris Semiconductor (Mountaintop, PA) on a system composed of SiC SBDs in an IGBT-driven inductive switching circuit showed that switching energy was reduced by a factor of four over PiN diodes.

Up till now SiC has made few inroads into the semiconductor industry, despite its manifest advantages. However, with the advent of larger, lower-cost wafers this looks set to change.

References

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